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Summary

The skin-friction drag of compliant coatings was measured using an axi-symmetric test model in a water tunnel for flow speed up to 4.5 m/s at the Reynolds number of 2.3 million. There were measurable drag reductions for up to 3% from three out of five compliant coatings tested. Only one coating showed a small drag increase, and the other had no change in drag. For all the tests, the 95% confidence level in measured drag reduction was ±1 % for flow velocities between 2.5 and 4.5 m/s. The error analysis suggested that the uncertainty was progressively increased with a reduction in flow velocity.

1. Introduction

The concept of drag reduction by compliant surfaces originates with the work of Kramer [1] who observed that a dolphin can swim at an exceptionally high speed. Kramer's experiments [2-5] indeed showed a substantial reduction in drag of up to 50% using compliant coatings modelled from a dolphin's skin. However, all the investigators who tried to repeat Kramer's work have failed. Meanwhile, Benjamin [6] examined the possibility of obtaining a drag reduction in fully turbulent boundary layers. A series of wind-tunnel experiments carried out at the University of Oklahoma [7-9] were reported to have shown turbulent drag reduction up to 50%, but these results could not be repeated in other tests [10,11]. Chung & Merrill [12] conducted an experiment using a rotating disc with a silicon-polymer coating for which a substantial drag reduction was observed. However, it is not certain whether the flow was laminar or turbulent in this experiment owing to the absence of velocity measurements. Taylor [13] and Falco & Chu [14] carried out experiments in which they claimed to have obtained drag reduction in turbulent boundary layers. The compliant coatings used in these investigations were very soft, so that deformations of the compliant surfaces could have caused pressure gradients that might have affected the drag measurements.

In 1980s, a Russian group at the Institute of Thermophysics has conducted a series of field tests of compliant coating, indicating that they have obtained a turbulent drag reduction of up to 20 % [15,16]. Lee *et al.* [17] of USA conducted an investigation in early 1990s, where a significant reduction in turbulent intensity was observed across the boundary layer over the compliant surface. About the same time, a careful study of turbulent boundary layer over the compliant coating was carried out by Choi *et al.* [18,19]. The results of floating balance measurement by Choi *et al.* showed that the turbulent skin-friction drag is reduced by up to 7 % by Coating 1. The second compliant coating showed only a marginal drag reduction at the lower end of the velocity range with a slight increase at higher velocities. The experimental conditions and material properties of coatings used in previous investigations by Kulik *et al.* [16], Lee *et al.* [17] and Choi *et al.* [19] are summarised in table 1.

In order to verify the turbulent drag reduction performance of compliant coating, a three-nation research collaboration between UK, US and Russia was carried out, where the same batch of compliant coatings were tested in three separate hydrodynamic facilities at the same time. This report contains the results obtained by the UK group.

Table 1. Boundary layer parameters and the material properties of the compliant coating in the previous studies.

	Kulik *et al.* [16]	Lee *et al.* [17]	Choi *et al.* [19]
U m/s	6.0 ~ 15.0	0.15 ~ 0.51	2.0 ~ 6.0
ρ kg/m^3	2.1x10^3	1.0x10^3	2.1x10^3
E Pa	3.7x10^6	0.68x10^3	2.8x10^6
H mm	2.5 ~ 7.0	38.0	7.0
C_T m/s	24.0	0.47	20.9
f_0 Hz	1.5x10^3 ~ 4.2x10^3	5.7	1.3x10^3
t_0^+	26 ~ 74	5 ~ 63	5 ~ 44
U/C_T	0.25 ~ 0.63	0.32 ~ 1.1	0.096 ~ 0.29

2. Experimental set-up

A water flume at the University of Liverpool was used for the present tests. This test facility can be used as an open channel or a closed water tunnel when a cover is fitted over the flume. The basic open channel arrangement of this facility allows easy access to the test section which measures 1.37 m wide x 0.84 m deep x 3.66 m long, thereby minimising the setting-up time of the experiments. The flow velocity of the flume can be controlled from a minimum speed of 0.03 m/s to the maximum of 6.1 m/s. The free-stream turbulence level of the water flume is 3%.

A test model was produced during the present investigation to accommodate small compliant cylinders (76.2mm diameter, 298mm long). This is identical to the model used in Russia (Institute of Thermophysics) and in USA (NUWC), whose details are shown in figure 1. The model consists of three parts: a flat nose section (219mm long), a test section (298 mm long) and a tail section (206 mm long). The skin-friction force is measured by a set of strain-gauge balance within the test model housing. Most of the test model parts were made of UPVC to reduce their weight and to prevent corrosion of the body surface in water. Three 0.65 mm thick disks were sandwiched between the nose and frontal section of the model to tip the boundary layer to promote turbulence and to fix the transition point. The Reynolds number based on the protrusion height (0.5 mm) of the disks was 1000 at the flow velocity of 2m/s, which is greater than the value (Re = 900) for a two-dimensional trip to be fully effective [23].

A set of compliant coatings was produced by the Institute of Thermophysics in Russia, which was transported to the UK for hydrodynamic tests. The set consisted of five cylinders, of which one cylinder (Coating 42) was damaged on transit. Table 2 shows the thickness and material properties of the coatings together with the information on the timing of the experiments (in days from production). Material properties shown in the table were measured in Russian after 11 days from production for Coatings #32 and #42, and after 25 days for the rest of coatings (Coatings #52, #51 and #22).

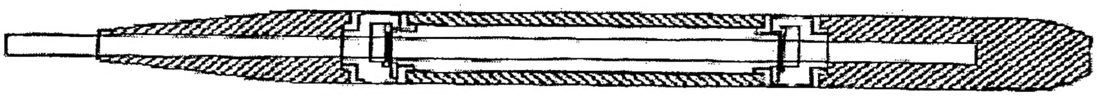

Figure 1. Test model used for the drag reduction study.

Table 2. Material properties of compliant coatings being investigated. Elasticity and loss tangent are quoted for quasi-equilibrium values at $f = 1$ Hz.

UK code	Material	Thickness mm	Density kg/m^3	Elasticity MPa	Loss tangent	Fundamental frequency kHz	Days from production
#32 Pink	N3A	5	2.14x10^3	1.75 @11days	0.185 @11days	1.43	129 days
#42 Pink	N3A	6	2.14 x10^3	1.75 @11days	0.185 @11days	1.19	199 days
#52 Clear	N5	3	1.00 x10^3	0.88 @25days	0.10 @25days	2.47	90 days
#51 Clear	N5	5	1.00 x10^3	0.88 @25days	0.10 @25days	1.48	125 days
#22 Clear	N5	7	1.00 x10^3	0.88 @25days	0.10 @25days	1.06	110 days

3. Results

The drag forces were measured for each of compliant coatings at the flow speed of 0, 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5 m/s. The measurements were repeated for three times, and the averaged values are shown in figure 2 (Coating #22), figure 4 (Coating #32), figure 6 (Coating #42), figure 8 (Coating #51) and figure 10 (Coating #52). Error bars in each figure indicate the standard deviation in the drag measurements at each speed. The corresponding data for the rigid surface test are shown in figure 12. Although an effort was made to remove the offset of strain-gauge balance during the calibration, there were still some remaining offsets, giving non-zero drag at zero velocity. Therefore, we fit third order polynomials through measured data points to determined the offset, which was subtracted from the original data. Figure 13 summarises all the drag values, which are compared with those of based line test using a rigid surface. The percentage drag reductions for each of five coatings were then obtained from these data, which are shown in figure 3 (Coating #22), figure 5 (Coating #32), figure 7 (Coating #42), figure 9 (Coating #51) and figure 11 (Coating #52). Figure 15 gives a comparison of all the compliant coatings in terms of drag reduction performance. The drag reduction in these figures is given by $(C_{D0} - C_D)/C_{D0}$ in percentage values, where C_D and C_{D0} are friction drag coefficient of compliant coatings and of rigid surface, respectively.

We found that there are measurable drag reductions, although small, from some of the coatings tested, notably for Coating #51 (see figure 9) for up to 3%. Coating #52 (figure 11) also has some extent of drag reductions for $U = 1$ to 3 m/s. Coating #42 (figure 7) shows some drag reductions at flow speeds up to 3 m/s. At higher flow speeds, however, drag of Coating #42 increases somewhat probably due to the roughness effect as a result of the damage sustained during transit from Russia to UK. Drag values of Coating #22 (figure 3) were similar to those of rigid surface, although a small reduction in drag was observed for flow velocities less than 1.5 m/s. The only compliant coating that gave drag increase throughout the velocity range of the present test was Coating #32 (figure 5). The error analysis that has been carried out in the present study indicates, however, that the uncertainty in drag reduction values is progressively increased with a reduction in flow velocity. This is because the error in measured drag is nearly constant at all flow velocities, while the skin-friction drag of the test cylinder increases proportional to the flow velocity squared. The standard deviation of drag measurements was approximately 0.0065 N, which is nearly equal to the skin-friction drag value at $U = 0.5$ m/s. The 95% confidence level in drag reduction is ±1 % for $U = 2.5$ to 4.5 m/s, ±5 % for $U = 0.75$ to 2.0 m/s, and ±15 % for $U =$ 0.5 m/s. The drag reduction value at $U = 0.25$ should not be relied on, as the 95% confidence level exceeds 100% in all the coatings tested.

Figure 14 presents the friction drag coefficient C_D against the flow speed U, where C_D value shows a monotonic decrease with an increase in the flow speed. This confirms that the boundary layer over the test surface (either the rigid or compliant coating) was fully turbulent owing to the trip device at the nose of the test model. If the boundary layer were not turbulent, we would have seen an increase in C_D value at the transition region where the flow will change from laminar to turbulent. Indeed, the skin-friction drag over the rigid surface is very similar to that of empirical data [24] for $U > 1$ m/s. The discrepancy between the measured C_D value and the empirical value at low speed less than 1m/s may be due to the progressive measurement errors as discussed above. Slightly smaller values in C_D could be due to the trip mounted at the nose section of the test model, which may have increased the virtual origin of the boundary layer development through an increase in the boundary layer thickness.

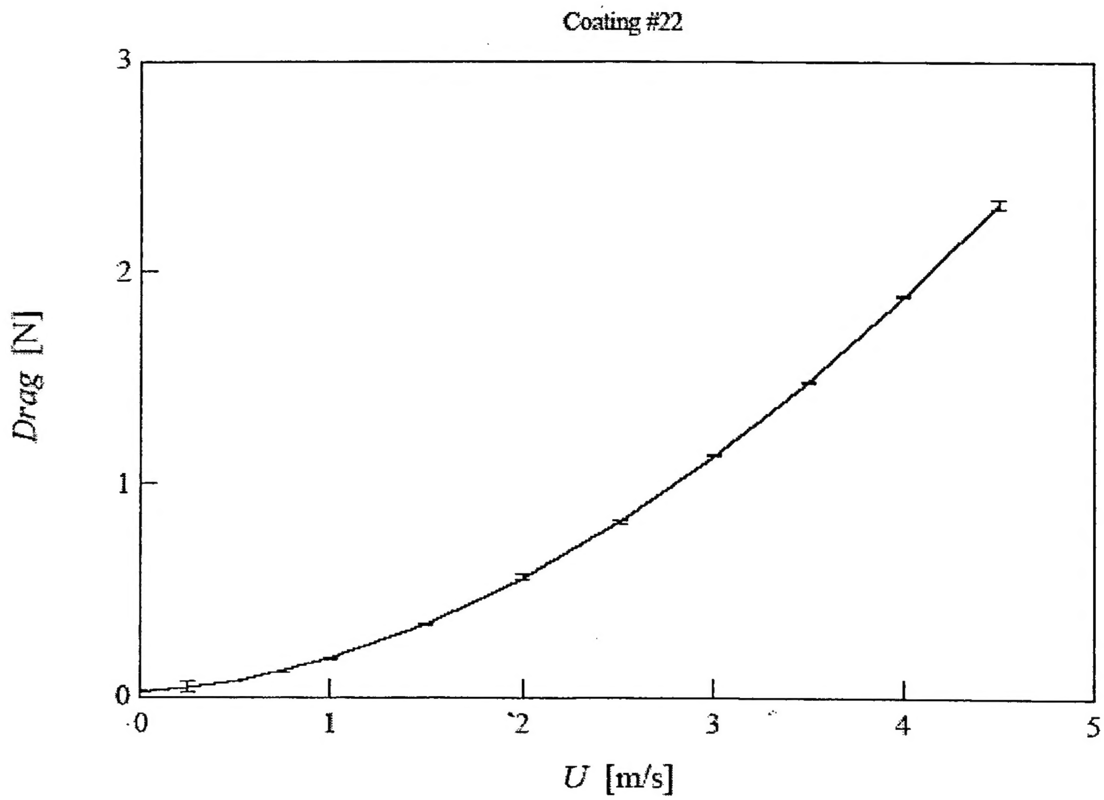

Figure 2. Skin-friction drag of Coating 22. Error bars indicate standard deviation in measured values.

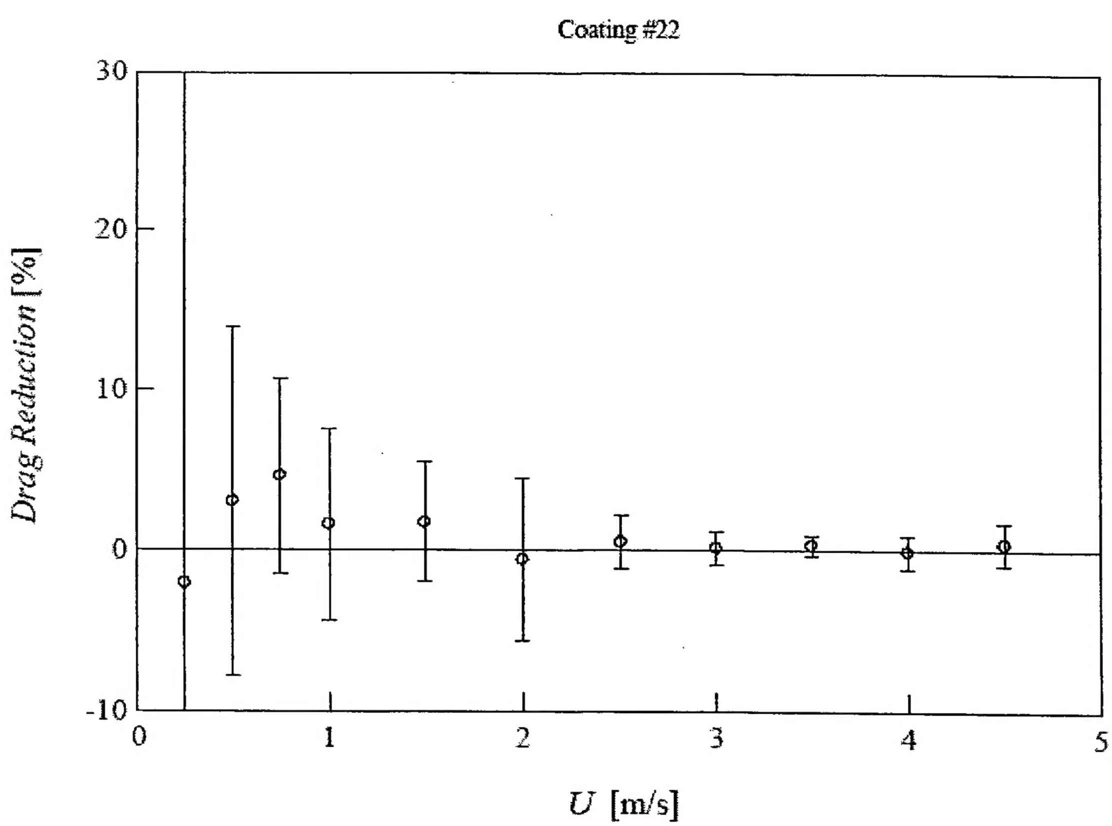

Figure 3. Reduction in skin-friction drag of Coating 22. Error bars indicate 95% confidence level.

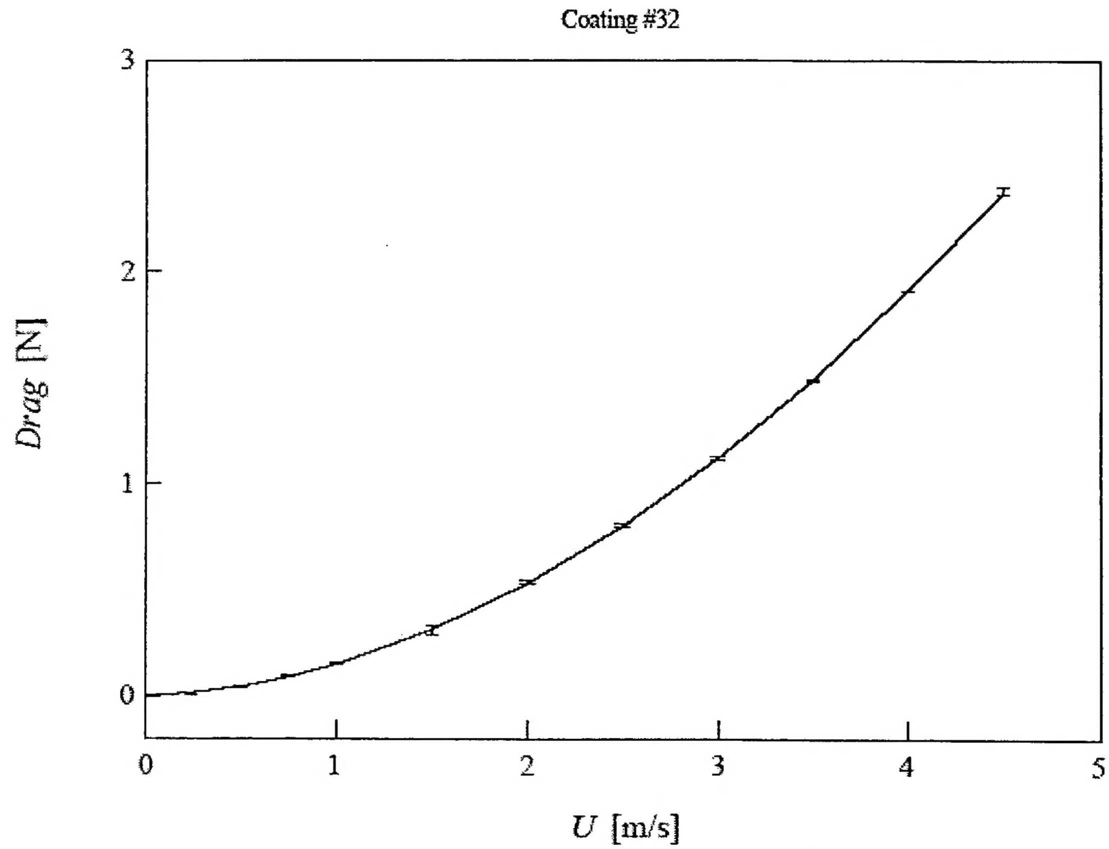

Figure 4. Skin-friction drag of Coating 32. Error bars indicate standard deviation in measured values.

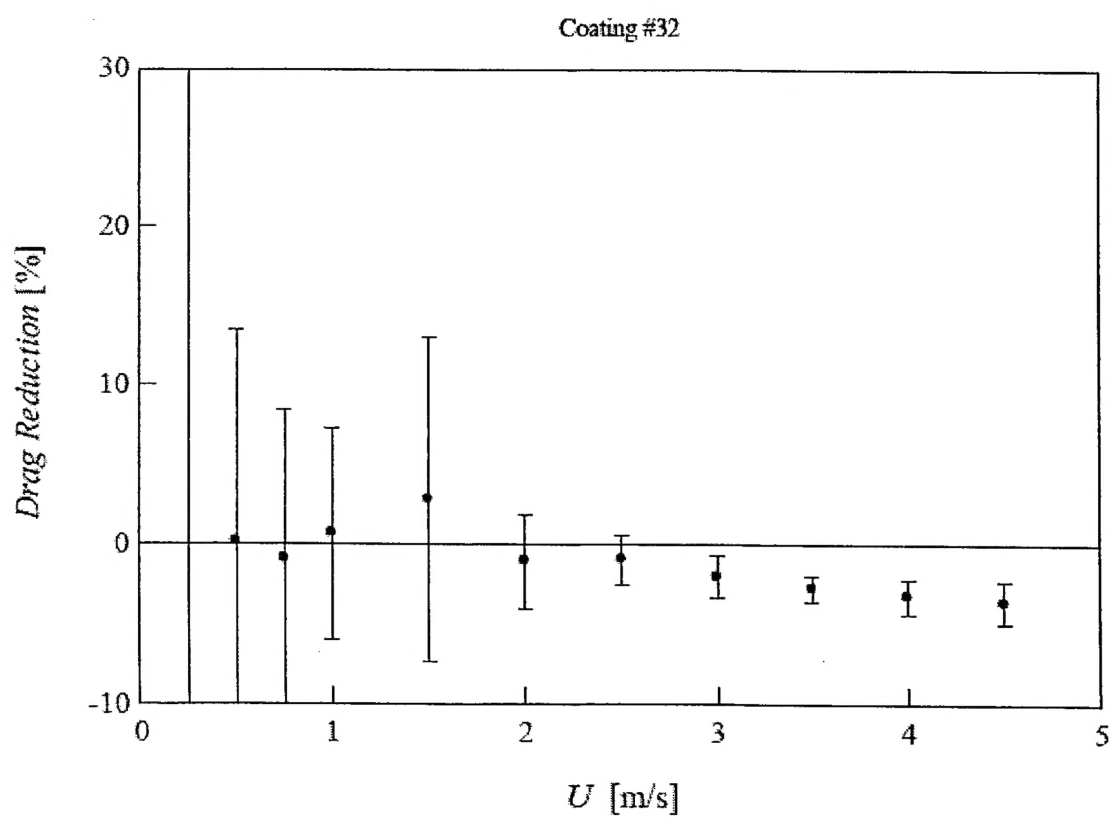

Figure 5. Reduction in skin-friction drag of Coating 32. Error bars indicate 95% confidence level.

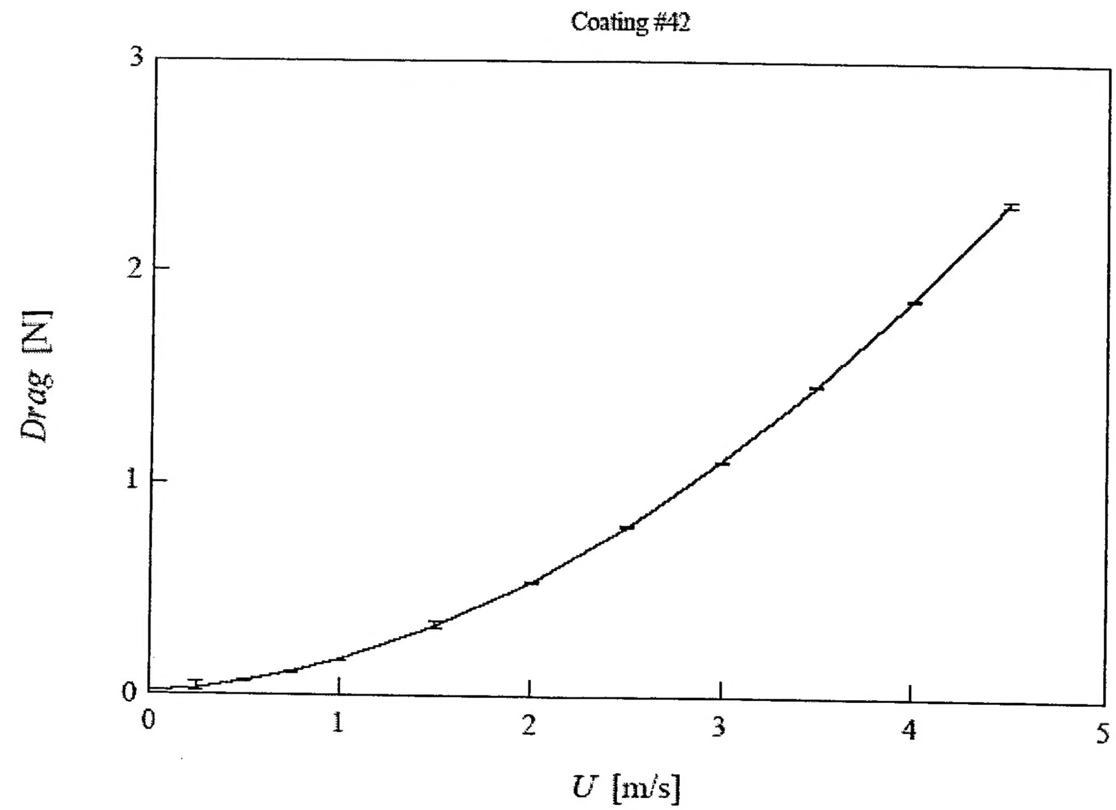

Figure 6. Skin-friction drag of Coating 42. Error bars indicate standard deviation in measured values.

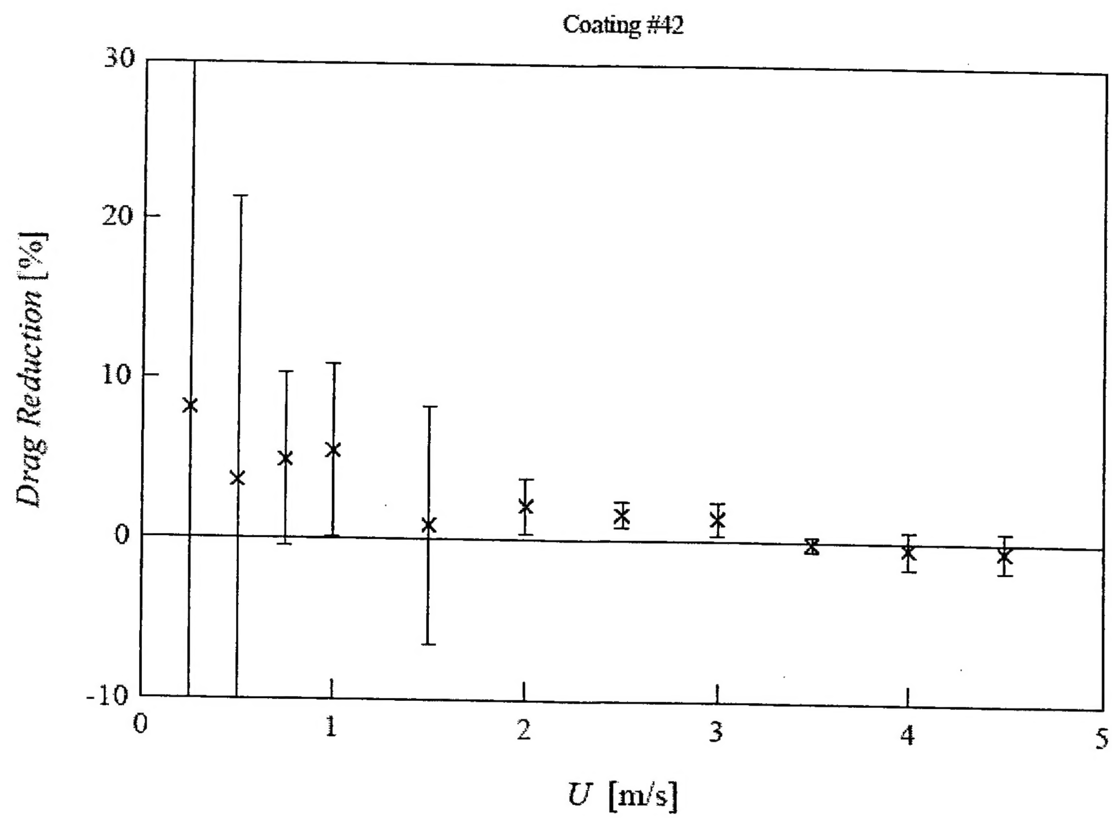

Figure 7. Reduction in skin-friction drag of Coating 42. Error bars indicate 95% confidence level.

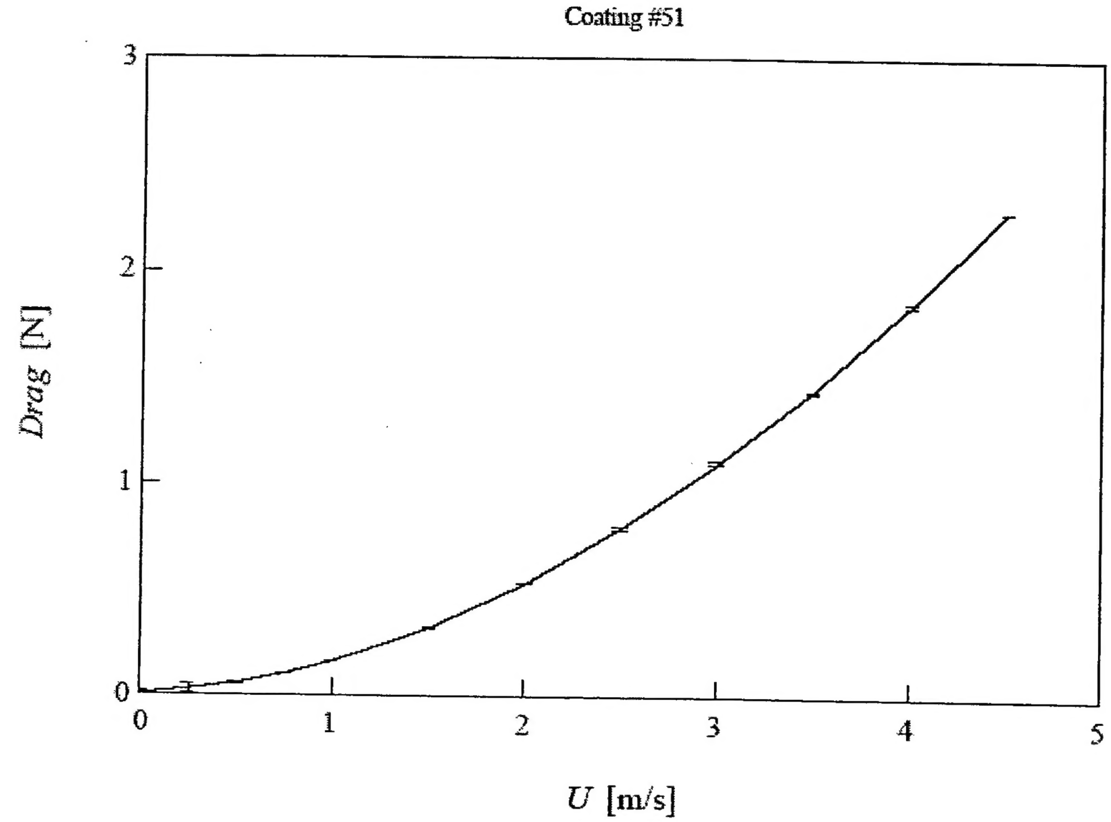

Figure 8. Skin-friction drag of Coating 51. Error bars indicate standard deviation in measured values.

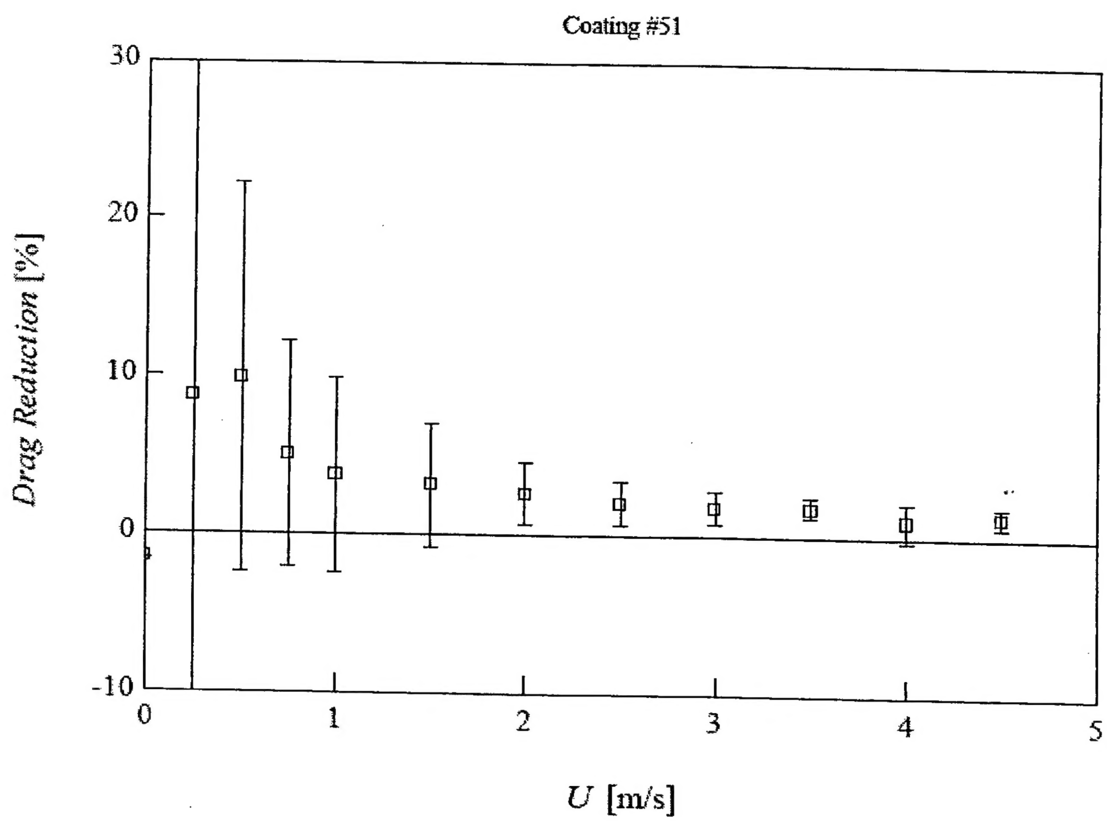

Figure 9. Reduction in skin-friction drag of Coating 51. Error bars indicate 95% confidence level.

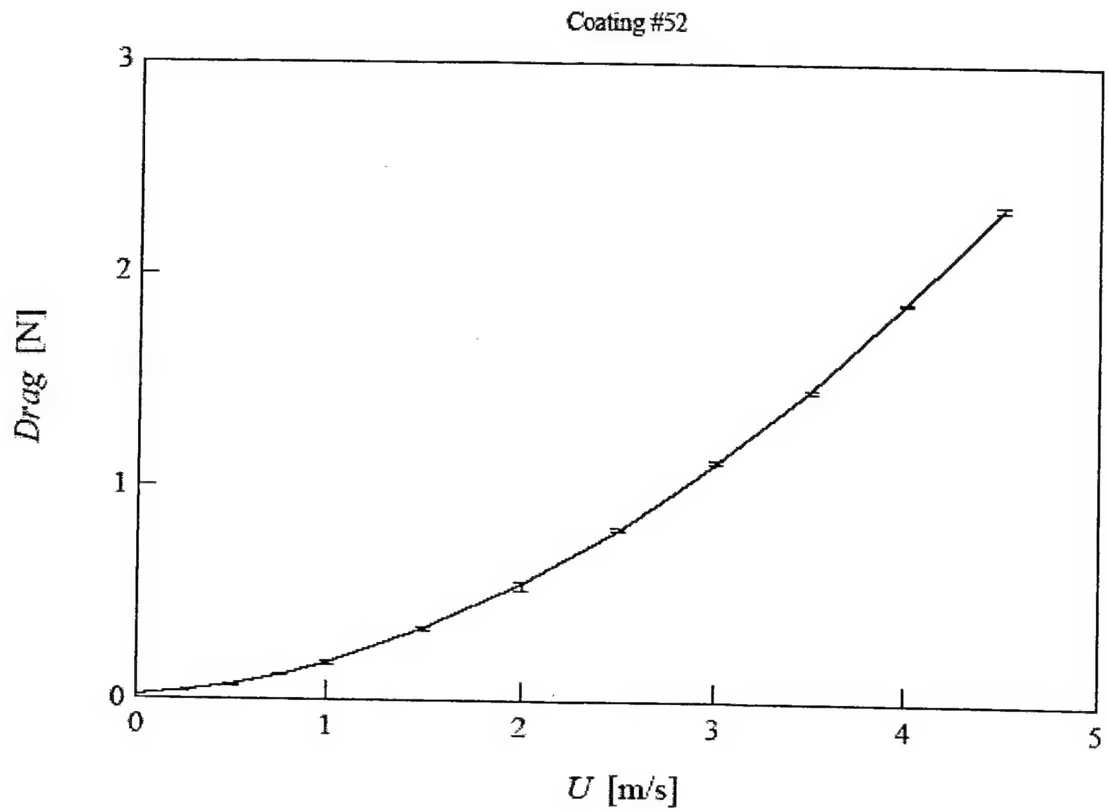

Figure 10. Skin-friction drag of Coating 52. Error bars indicate standard deviation in measured values.

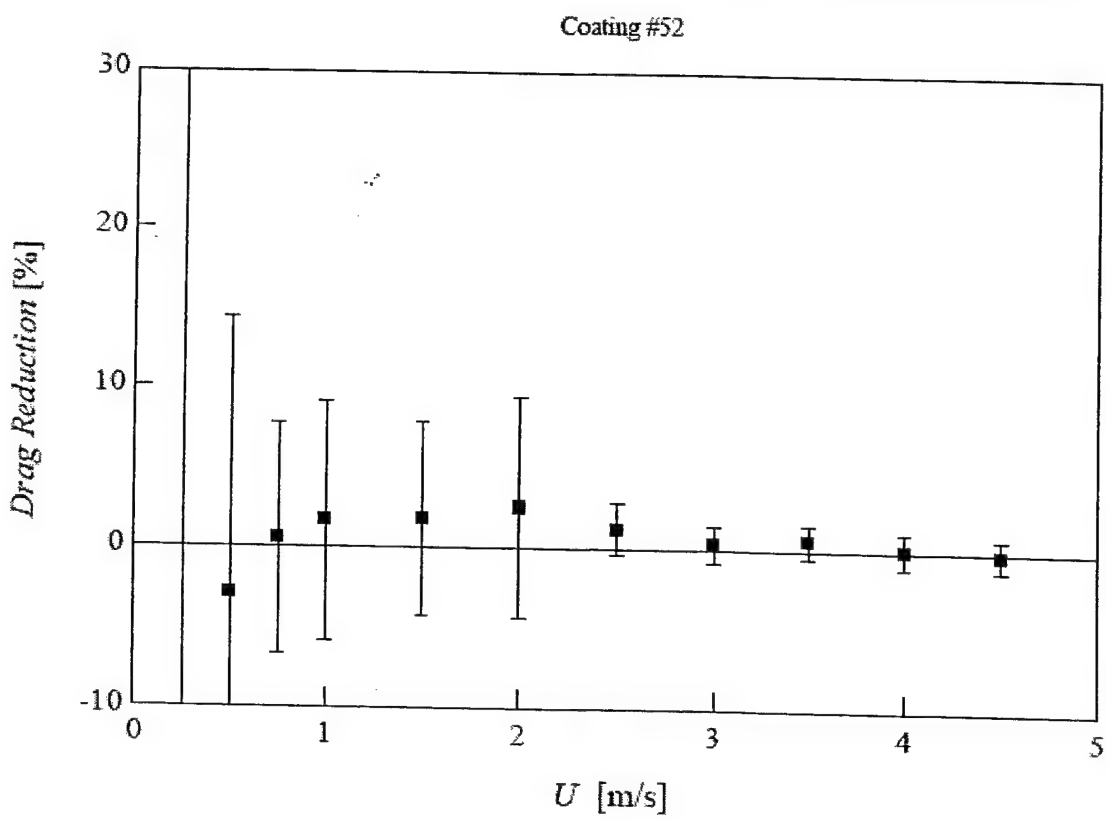

Figure 11. Reduction in skin-friction drag of Coating 52. Error bars indicate 95% confidence level.

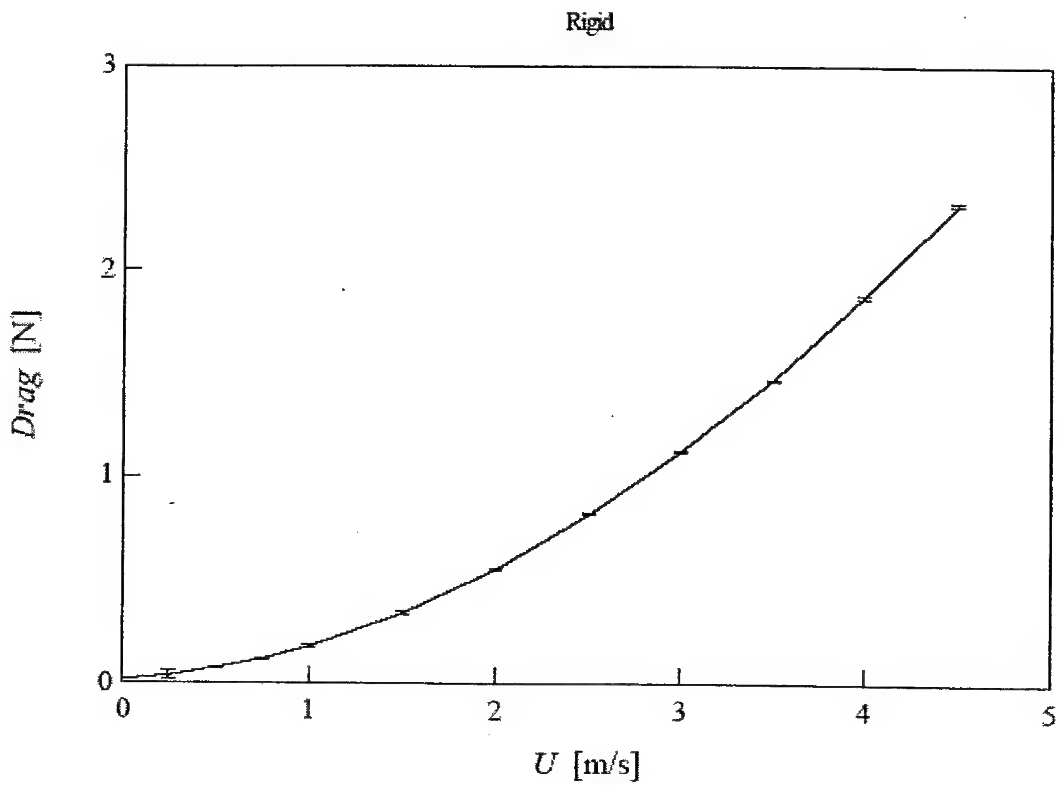

Figure 12. Skin-friction drag of rigid surface. Error bars indicate standard deviation in measured values.

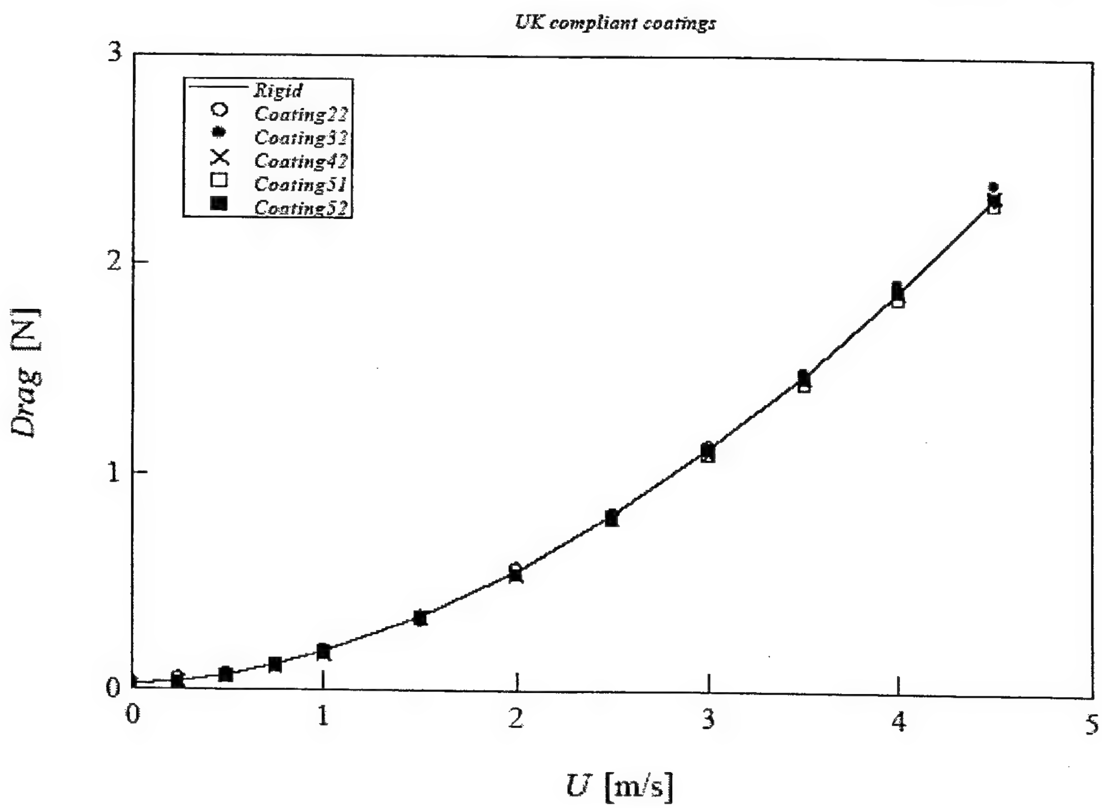

Figure 13. Skin-friction drag of compliant coatings.

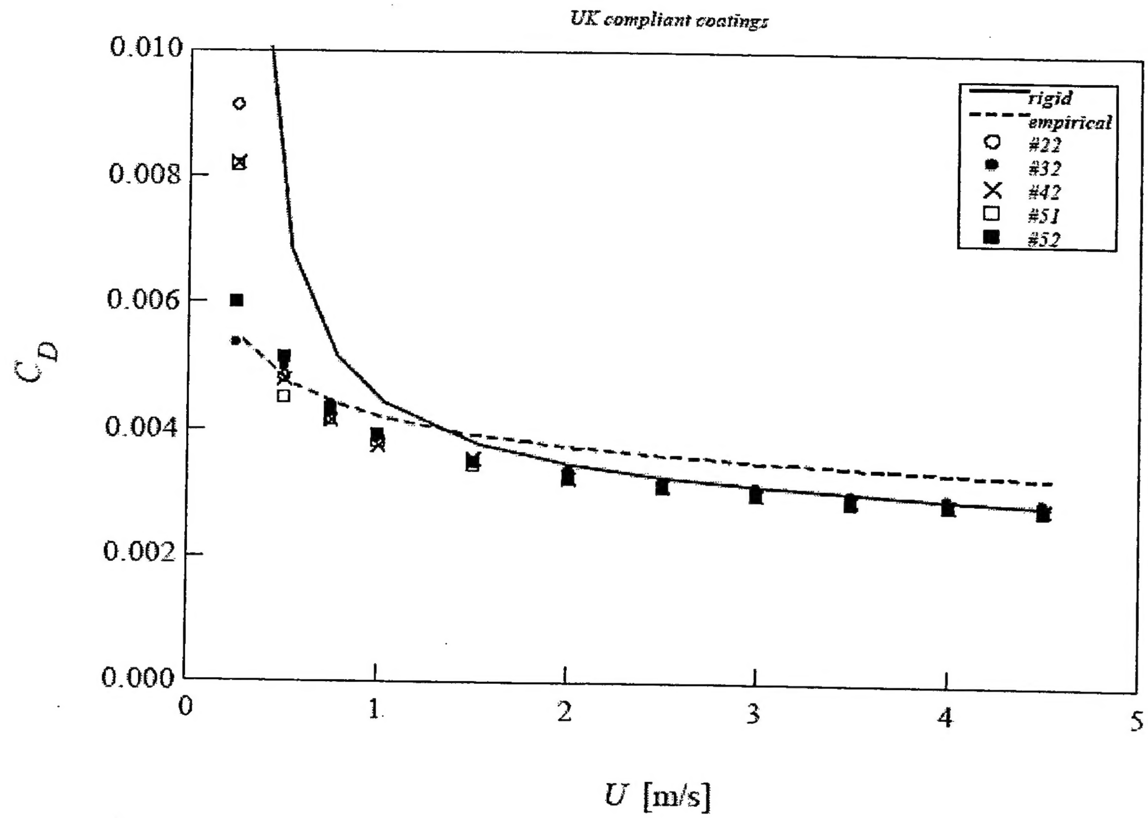

Figure 14. Skin-friction coefficient of compliant coatings in UK tests.

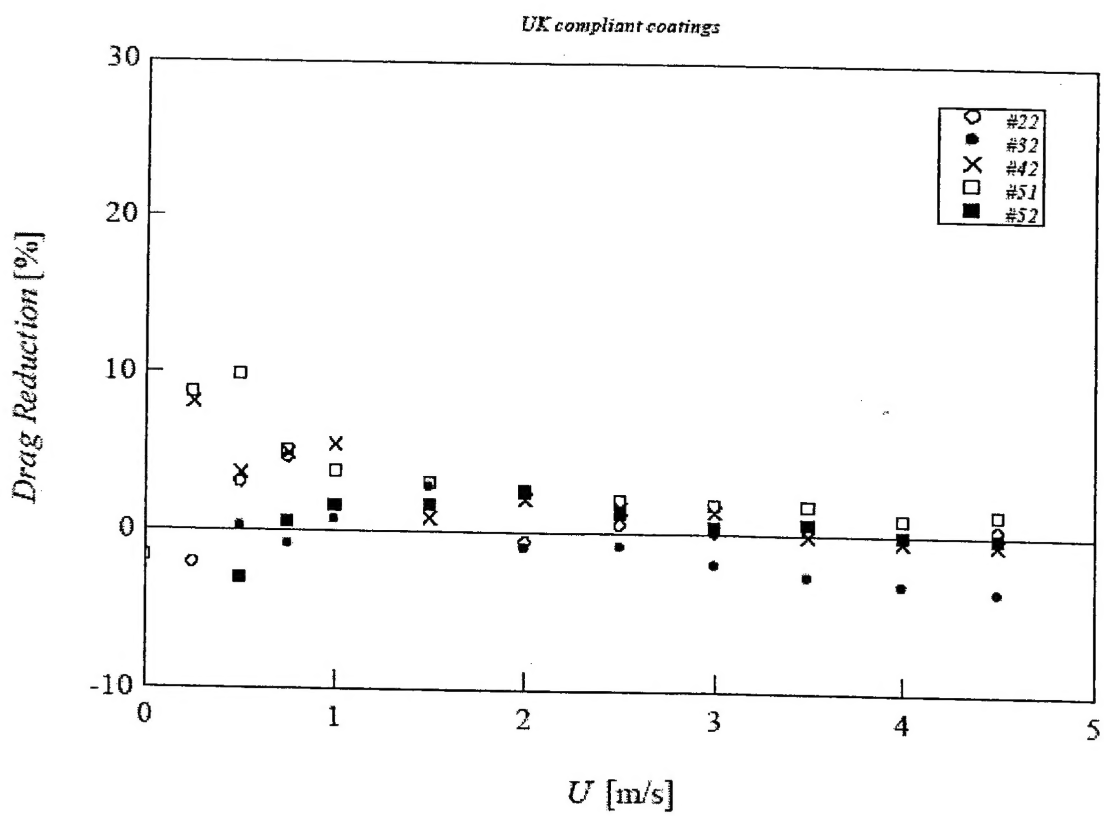

Figure 15. Drag reduction of compliant coatings.

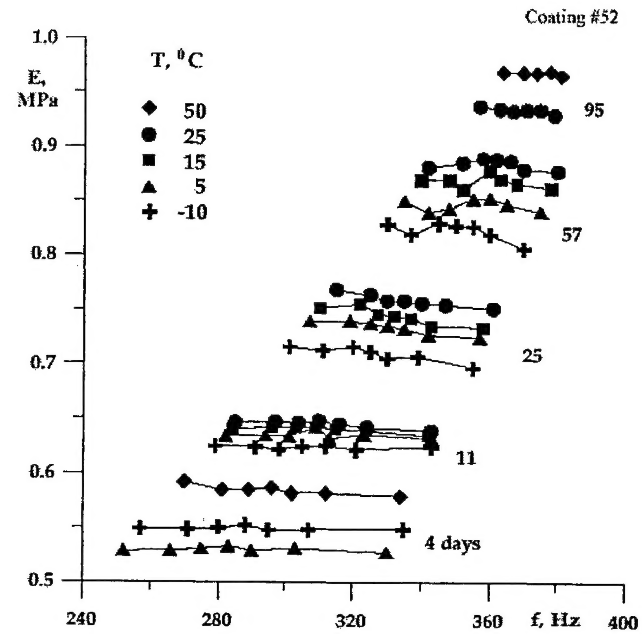

Figure 16. Change in the modulus of elasticity due to aging of Coating 52.

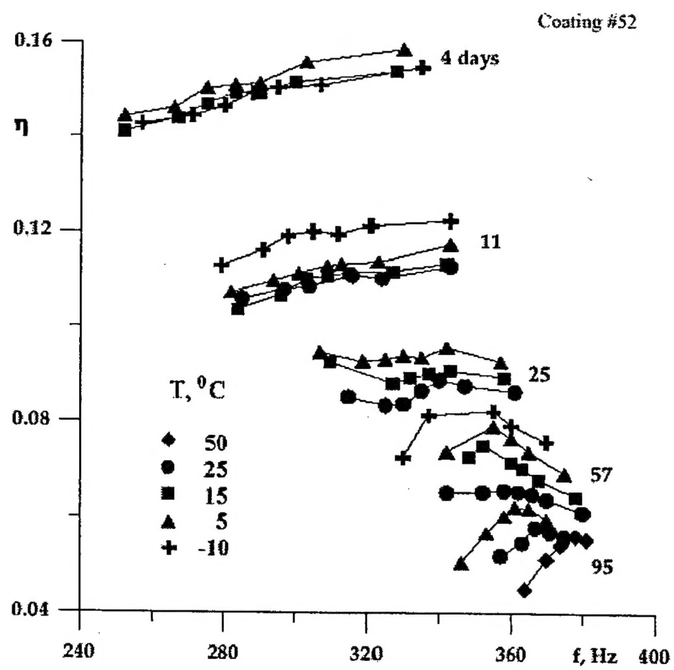

Figure 17. Change in the loss tangent due to aging of Coating 52.

4. Discussions

For homogeneous, single-layer material with the modulus of elasticity E, density ρ and thickness H, the fundamental frequency of the coating's longitudinal vibration is given by $f_0 = \sqrt{E/\rho}/4H$ [16]. The corresponding non-dimensional period of the coating's fundamental frequency is given by $t_0^+ = f_0^{-1}u^{*2}/\nu$. Here, the effect of the viscoelasticity on the vibrational characteristics is usually small, which can often be neglected [22]. The fundamental frequencies of compliant coatings tested in the present study (see table 2) were in the range of $f_0 = 1.0 \sim 2.5$ KHz, which are similar to those of coatings tested by Choi *et al.* [19] and Kulik *et al.* [16]. In terms of the non-dimensional period, they are in the range of $7 < t_0^+ < 23$ for the flow speed of $U = 2.5$ to 4.5 m/s. These values compare well with those of successful investigations (see table 1 for summary), where the non-dimensional period of the first harmonic of the compliant coating fell within $5 < t_0^+ < 74$. It is known [20, 21] that the period of the pressure pulse in the turbulent boundary layer during the sweep events is about $t_0^+ = 20$. Our data as well as those of Choi *et al.* [19] and Kulik *et al.* [16], therefore, suggest that the pressure pulse in the near-wall region of turbulent boundary layer is causing a resonance to the surface of compliant coating during the sweep events [22]. This is considered as the mechanism of turbulent drag reduction by compliant coating, and all test surfaces examined in the present study possessed the right resonant characteristics for drag reduction. It has been expected, therefore, that we would have clear drag reductions in the present study, but the results painted a rather complex picture; there are probably more to the simple analysis of fundamental frequency of compliant coatings in turbulent drag reduction. An answer to this question may lie on the aging of test materials.

Figures 16 and 17, which were obtained from the Institute of Thermophysics of Russia, show the aging profile of one of the coatings tested (Coating #52). The Coatings #51 and #22 are made of the same material as Coating #52, therefore the same aging characteristics should apply to those coatings. No information are currently available for the rest of coatings (Coating #32 and #42). Figures show the modulus of elasticity E (figure 16) and the loss tangent η (figure 17) as a function of the frequency f, with time (given in days) since the manufacturing of coatings as a parameter. In only 3 months the coating hardened (the modulus of elasticity was increased) by twice, while the material damping reduced (the loss tangent was reduced) to one third. The fundamental frequency of the coating's longitudinal vibration is proportional to the square root of the modulus of elasticity ($f_0 \sim \sqrt{E}$), therefore the consequence of material hardening (increase in E) by aging was to increase the effective frequency range of compliant coating. This means that the optimum flow speed for drag reduction would be increased with time. We can obtain the actual module of elasticity for Coatings #52, #51 and #22 at the time of experiment by extrapolating the data in figure 16, which is estimated to around $E = 1.2$ MPa. However, this increase in E will increase the optimum flow speed only by 8%, which is too small to explain the differences observed in the present study.

It seems that the reduction in loss tangent due to aging (by two thirds in three months) may be the crucial factor in explaining the present results. Unfortunately, there are no satisfactory theories for turbulent drag reduction based on loss tangent at the moment. This is an important area of future investigation for the understanding of drag reduction using compliant coating.

5. Conclusions

The skin-friction drag of compliant coatings was measured in a water tunnel for flow speed up to 4.5 m/s, with a corresponding Reynolds number of 2.3 million. The axi-symmetric test model had a transition trip at the end of the nose section, ensuring that the boundary layer over the cylindrical test section was fully turbulent. This was confirmed from the behaviour of the friction drag coefficient C_D against the flow speed U, where C_D value showed a monotonic decrease with an increase in the flow speed. Indeed, the skin-friction drag over the rigid surface was very similar to that of the empirical data. There were measurable drag reductions for up to 3% from three out of five compliant coatings tested. Only one coating showed a small drag increase, and the other had no change in drag. For all the tests, the 95% confidence level in drag reduction was ±1 % for U = 2.5 to 4.5 m/s. The error analysis suggested that the uncertainty was progressively increased with a reduction in flow speed.

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